EVIDENCE FOR A TSUNAMI GENERATED BY AN IMPACT EVENT IN THE NEW YORK METROPOLITAN AREA APPROXIMATELY 2300 YEARS AGO

A Final Report of the Tibor T. Polgar Fellowship Program

Katherine T. Cagen

Polgar Fellow

Harvard College
Harvard University
Cambridge, MA 02138

Project Advisor:

Dallas H. Abbott
Lamont Doherty Earth Observatory of Columbia University
Palisades, NY

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ABSTRACT

Oceanic impacts such as the one discussed in this paper, which we propose occurred approximately 2300 years ago in the Atlantic Ocean, are a poorly understood phenomenon. Though the Earth is seventy percent covered with water, scientific investigations have focused on continental events. This is in part due to the difficulties inherent in examining submarine impact structures. Oceanic impacts lack many of the known features of continental events. However, oceanic impacts, unlike their continental counterparts, produce catastrophic tsunami events that may be used to identify them. Recent discoveries point to a tsunami event that affected the New York metropolitan area approximately 2300 years ago (Goodbred et al. 2006). Here it is shown that impact ejecta found in the tsunami deposit layer underneath the Hudson River indicate an oceanic impact as the source of the tsunami. The sharp resolution of the stratigraphic study of the cores suggests that the sediment containing impact ejecta was deposited in a tsunami-like event, rather than being reworked from an older event. Individual ejecta grains were identified through an examination of samples from the tsunami layer with optical and electron microscopy, as well as compositional analysis via energy dispersive X-ray spectroscopy. Carbon and aluminum silicate impact spherules were found in the samples. Also present in the samples were shock-metamorphosed phases of feldspar, ilmenite, and olivine exhibiting planar deformation features and Brazil twinning consistent with studies of known impact ejecta. TEM studies of the spherules revealed the presence of associated hexagonal nanodiamonds, also known as lonsdaleite, which are uniquely related to shock formation. In addition, the New York area lacks the extreme seismic and volcanic activity that might produce similar results, leaving a hypervelocity bolide impact as the most likely source for the tsunami event and associated impact ejecta. As oceanic impacts pose a serious threat to coastal communities around the world, it is necessary to understand both their frequency and effects. It is hoped that this method of identifying an oceanic impact via the ejecta found in tsunami deposits will improve our understanding of submarine impact events.

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INTRODUCTION

We propose that the source of the tsunami event recently discovered to have occurred in the New York area approximately 2300 years ago was the submarine impact of a hypervelocity bolide, a type of event that is poorly understood by the scientific community. Though the Earth is approximately seventy percent covered by water, less than twenty percent of known impact craters are located underwater (Gersonde et al. 2002). This discrepancy is the combined result of a lack of investigation into submarine impacts and the difficulty inherent in identifying them. The geological structures produced by submarine impacts are difficult to find, and are often changed by erosion and blanketed by new sediment. They also differ greatly from their continental counterparts, with which scientists are more familiar (Strelitz 1979). In the search for oceanic impacts, it is necessary to create more reliable methods of identification, understanding that the characteristics of submarine impacts can vary greatly from those of continental events.

One of the most unique features of a submarine impact is the tsunami. A submarine impact can produce a megatsunami wave with a run-up in the hundreds of meters, depositing oceanic sediment and impact ejecta (terrestrial material recognizably altered by the pressure and heat of an impact; impact debris) kilometers from the impact site (Bryant 2001; Crawford and Mader 1998). It is therefore possible to identify an impact through the traces that the ensuing tsunami left in the geological record. The deposition of sediment from tsunami waves of the magnitude produced by bolide impacts occurs over an incredibly short interval, from minutes to a few hours, rarely even days (Dypvik and Jansa 2003). This sudden deposition produces a well-defined, visible contact between the tsunami deposit and the underlying sediment.

Goodbred et al. (2006) provide compelling evidence for a tsunami event in the New York metropolitan area approximately 2300 years ago. They record horizontal runups of hundreds of meters inland from Long Island's Great South Bay, which correspond to an abnormally large wave. We hope to expand on Goodbred et al.'s work on samples from the Great South Bay by further detailing the extent of the tsunami's effects up the Hudson River and establishing the origin of the tsunami to be a hypervelocity bolide impact by discovering evidence for an impact in material deposited by the tsunami further up the Hudson River. Sampling of the tsunami layer in the Hudson has revealed multiple pieces of impact ejecta (impact debris), including shocked minerals and impact spherules. These ejecta strongly suggest that an impact event around 2300 years ago produced a tsunami that hit the New York metropolitan area.

METHODS

Sediment samples of the tsunami layer are from core samples of the bottom of the Hudson River near Piermont, New York. Samples were taken from the layer in sediment cores CD01-01, CD01-02, SD30, and VM 32-2 from the Hudson River (see Figure 1). The thickness of the layer ranged from approximately half a meter in CD01-02 to four centimeters in VM32-2. Both the macroscopic descriptions of the cores and photographs of the cores were used to identify potential ejecta layers, specifically descriptions that indicated the presence of glass or large coarse fractions and core photographs that showed sharp contacts between layers of sediment, indicative of a sudden deposit of material like that from a tsunami.

Individual samples generally span two to three centimeters within the core. Control samples were taken from above and below prospective tsunami deposit layers. Samples were sieved with de-ionized water, separated into >150 micrometer, >63 micrometer, and >38 micrometer fractions, and then dried in an oven at 60° Celsius. The >150 micrometer fraction (coarse fraction) was then examined with a Nikon SMZ2800 optical microscope. Grains that seemed to have an impact origin, including spherules, broken or strangelyshaped grains, quartz with shock lamellae, and magnetic fragments were selected for further examination. Selected grains were placed on mounts, which were then examined with scanning electron microscopy. After the samples were coated in platinum with a Cressington SputterCoater 208, high-magnification photographs were taken with a Philips ESEM (Environmental Scanning Electron Microscope). Elemental analysis was also performed with an attached EDAX (Energy dispersive X-Ray analysis system). These analyses provide important insight about the nature of individual grains of ejecta, and therefore accompany the SEM photomicrographs. Final analysis was based on both the photographs and elemental analyses.

RESULTS

The impact ejecta found in the samples can be organized into four categories: impact spherules, shock-metamorphosed minerals, impact generated textures, and impact generated rocks.

Impact Spherules

Spherules are millimeter-sized glassy spheres composed of minerals that were melted in the impact and re-solidified in the near-vacuum left in the wake of the impactor (Melosh and Vickery 1991). Spherules of varying chemical compositions were found throughout the sampled tsunami layers.

Many of the spherules are composed primarily of carbon, though they vary in texture, appearing both vesicular (Figures 2 and 3) and glassy (Figures 4 and 5). Some of the carbon spherules contain mixtures of other elements, or have splash (once-melted minerals, visible in Figure 6) on their surfaces (Figures 4 through 7). We also found a spherule with many partially formed spherules (microspherules) on its surface (Figures 8 through 13). Some spherules, such as the spherule in Figures 12 and 13, exhibit quench texture, a surface of randomly oriented crystals that is produced by the rapid cooling of the melted spherule as it lands in the water and further solidifies the association of spherules with an impact event. The other spherules are composed primarily of silicate, SiO_2. Some of these, such as the spherule in Figures 14 and 15, have extraordinarily smooth surfaces. Others, such as the spherules in Figures 16 through 21, also exhibit quench texture or other surface features, such as the ilmenite needles in Figures 22 and 23.

Shock-metamorphosed minerals

Pressure on the host rock during an impact event can exceed over one hundred gigapascals at the point of impact. This immense pressure affects minerals in ways unique to hypervelocity bolide impacts, called shock-metamorphic effects. These changes are often visible as planar deformation features (PDF's) in quartz, feldspar, and other minerals. These features are visible in the feldspar in Figures 24 though 27 and the olivine in Figures 28 through 31. (Chao 1967, French 1998). Impact breccias are the result of several angular pieces of rock smashed together to form a single grain under immense pressure (French 1998). Though breccias are produced by several geological processes, the ilmenite in Figures 32 and 33 also exhibits classic shock-metamorphism, with offsets of curved lamellae similar to those of known shocked ilmenite specimens (Harris et al. 2005). Brazil twinning is a particular zig-zag pattern of shock lamellae produced under high pressure (Stöffler and Langenhorst 1994). It is clearly visible in Figures 26 and 27 that the lamellae are generally continuous and less than one micrometer apart. The olivine grain in Figure 28 also exhibits very closely spaced planar fractures, visible in the close-up (Figures 30 and 31).

Impact Generated Rocks

Ilmenite, or iron titanium oxide ($FeTiO_3$), has been found in two significant forms in the tsunami deposits. Figure 32 shows a shocked ilmenite breccia, while Figures 22 and

23 show nanoscale needle-like forms of ilmenite, both of which imply an impact origin for the tsunami.

Nanodiamonds

Nanodiamonds are formed under the intense pressure of impact, are incredibly rare and almost exclusively related to impact events. In particular, the form of diamond called lonsdaleite, which has a specific hexagonal structure, has been found exclusively associated with meteorites and impact events (Lipschutz and Anders 1961). Hexagonal-form nanodiamonds (Figures 34 through 37) were found associated with some of the carbon spherules from the tsunami deposit layers, and are visible as Transmission Electron Microscope images in Figures 34 and 36.

These nanodiamonds were identified as lonsdaleite through their electron diffraction patterns, as visible in Figures 35 and 37. These patterns are produced by observing the scattering of a beam of electrons due to the internal lattice structures of a grain. These patterns are therefore uniquely related to the internal structure of a grain, and in this case the hexagonal pattern allowed us to conclusively identify the nanodiamonds found with the associate spherules as lonsdaleite.

DISCUSSION

Spherules

The presence of spherules strongly suggests an impact origin; spherules are associated with numerous impact events, including events in Bosumtwi (Ghana), South Africa (Koeberl 1994, Lowe and Byerly 1986), and Western Austraila (Lowe and Byerly 1986). Spherules have also been found in the Barringer Meteorite Cater (Arizona) (Masaitis 2006) the Wabar crater (Saudi Arabia) (Mittlefehldt et al. 1992,) and the Lonar crater (India) (Murali et al. 1987). Spherules have been found in abundance in distal ejecta deposits from the Chicxulub impact, at the Cretaceous-Tertiary boundary (Powell 1998).

Spherules are particularly common in lunar materials, where their abundance may reflect the high frequency of small impacts due to the lack of a lunar atmosphere (Symes et al. 1998). In particular, carbon spherules similar to those found in this investigation were found at the site of a proposed impact that contributed to the Younger Dryas cooling (Firestone et al. 2007).

Shock-metamorphism

The shock-metamorphism discovered in the tsunami layer is a clear indicator of an impact event; impacts are the only natural source for such effects. In particular, the shock-metamorphosed ilmenite breccia (Figure 32) and feldspar with Brazil twinning (Figures 24 through 27) are undeniably the results of an impact. True shock metamorphism is unique to impact events, and therefore the presence of both shock metamorphism and brecciation is strongly indicative of an impact origin. Although widely spaced Brazil twinning can be produced by geological processes other than impacts, the spacing of the twin planes in Figures 26 and 27 indicates an impact origin. While a spacing of less than one micrometer is not uncommon for impact events, planes from other processes tend to be at least 10 micrometers apart and vary in continuity (Alexopoulos 1988; Koeberl 2002). Thus, the shock-metamorphosed feldspar in Figure 24, which exhibits Brazil twinning, clearly has an impact origin. The occurrence of planar fractures in olivine is also characteristic of shock metamorphism (Stoeffler 1972).

Impact Generated Rocks

The ilmenite breccia is a clear indicator of an impact event. Similarly indicative of an impact origin are the ilmenite needles exhibited in Figures 22 and 23. These ilmenite needles are very similar to ilmenite needles found in lunar craters (Heiken and Vaniman 1990) and have been identified in ejecta from impact structures on Earth

(Glikson and Allen 2004). Like spherules, the presence of nanoscale ilmenite needles in the tsunami deposits is indicative of an impact origin.

Nanodiamonds

Lonsdaleite is a particular hexagonal form of carbon that is exclusively related to impacts (Frondel and Marvin 1967; Lipschutz and Anders 1961). Nanodiamonds such as the ones found in this event have been found associated with a number of well-known impact structures, including the KT Boundary and the Younger Dryas impact event (Powell 1998; Firestone et al. 2007; Masaitis 1998; Koeberl et al. 1997; Heymann et al. 1966). Electron diffraction analysis has confirmed that the nanodiamonds found in the tsunami deposits are lonsdaleite, which is an unequivocal link between the tsunami and a hypervelocity bolide impact event.

Alternative Explanations

All of the evidence gathered so far supports an impact event. There is simply no other explanation for the tsunami layer, the shocked feldspar, the impact breccia, and the spherules. Though explosive volcanism and high-magnitude seismic activity can produce similar results, the lack of extreme volcanic and seismic activity in the New York area leaves an impact event as the only reasonable cause. Also, the grains show no signs of long-term erosion or transport by water, suggesting that they were produced near their depositional sites. Although the eastern United States has experienced several tsunami-like events during historical times, none in the New York metropolitan area have been of a magnitude comparable to the event described here (Lockridge et al. 2002). The Atlantic, unlike the Pacific, is not bordered by subduction zones, where earthquakes with large vertical offsets would displace enough water to generate a megatsunami (Lockridge et al. 2002). The lack of any source of explosive volcanism in the area further rules out volcanic activity as the source of the tsunami.

Location and Date

Though the proposed impact is submarine, the presence of quartz and K-feldspar, abundant on the continents but not on the seafloor, suggests an impact on the continental shelf. The tsunami layers vary in thickness from 10 to 200 centimeters, indicating proximity to the impact site. The presence of impact ejecta upriver indicates a serious local event, though we have not yet determined the upriver extent of the tsunami.

The date for the impact, approximately 2300 years ago, is given from carbon dating of material in the tsunami layer performed by Goodbred et al. (2006) This date is imprecise due to the lack of a reservoir correction for carbon dating in the Hudson. Future investigations will include more rigorous dating of the event.

CONCLUSION

Our examination of the Hudson River sediments strongly supports our supposition that the tsunami event was generated by an impact. We were able to establish widespread presence of impact ejecta, including spherules and shock-metamorphosed minerals. The presence of ejecta in multiple cores at 2300 B.P. indicates that there was a local impact event at that time. Our discovery of exclusively impact-related nanodiamonds (lonsdalite) at the same age further cements our impact hypothesis. We have conclusively determined that there was an impact event approximately 2300 years ago in the New York area. We hope in future studies to better document the extent of the resulting tsunami, its potential effects on the Hudson River area, and locate the impact site.

FIGURES

Figure 1. Location of core samples in the Hudson River

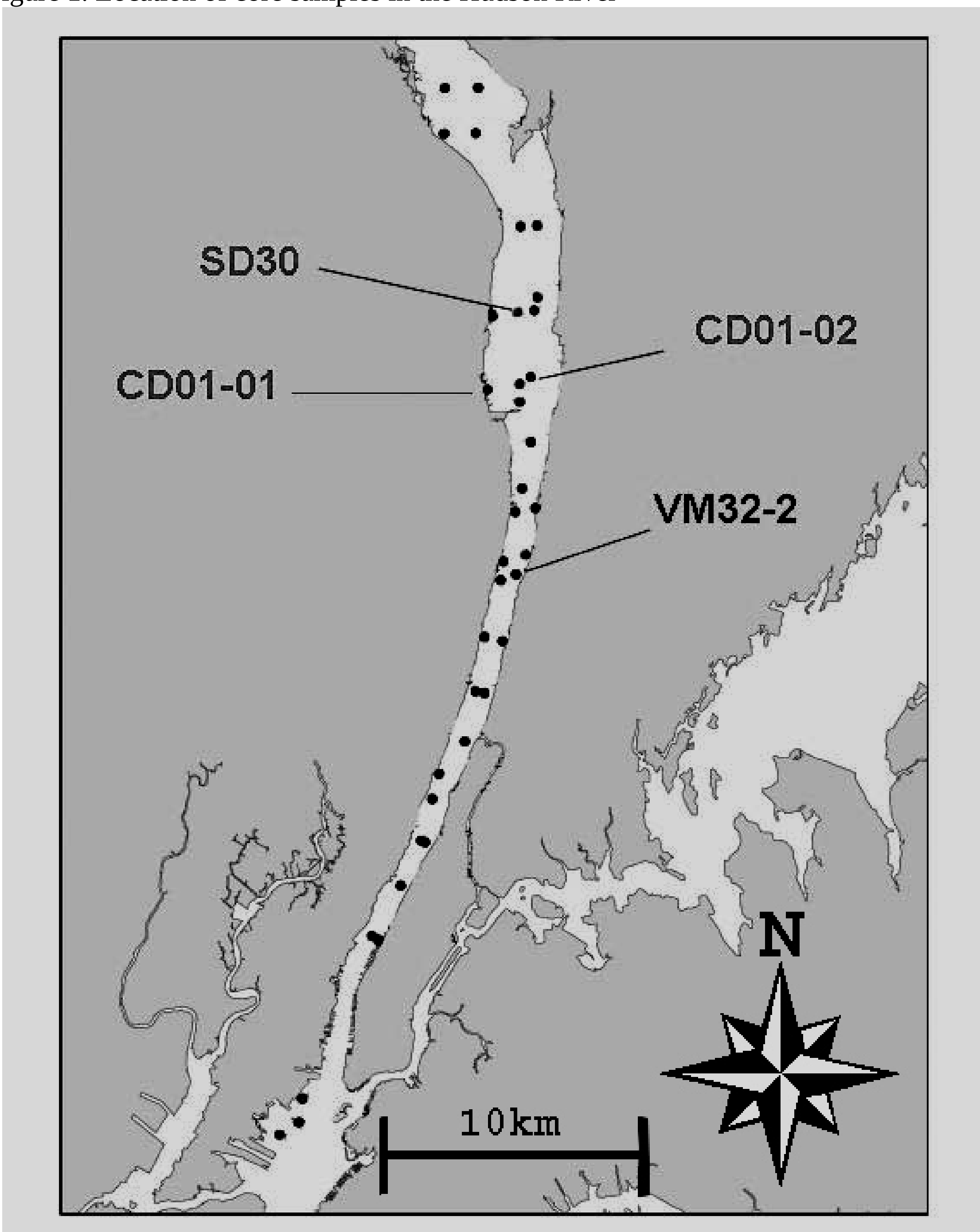


Figure 2. Vesicular carbon spherule

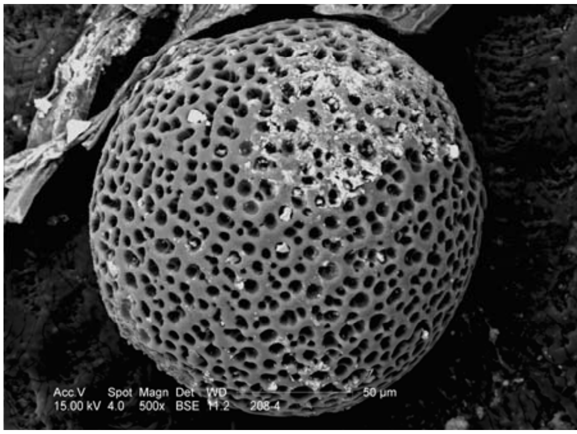


Figure 3. Chemical composition of spherule in Figure 2

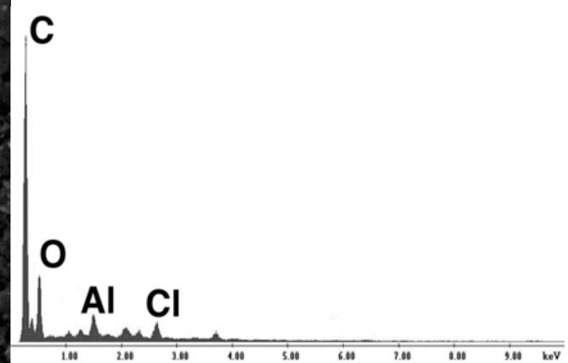


Figure 4. Smooth carbon spherule with pyrite splash

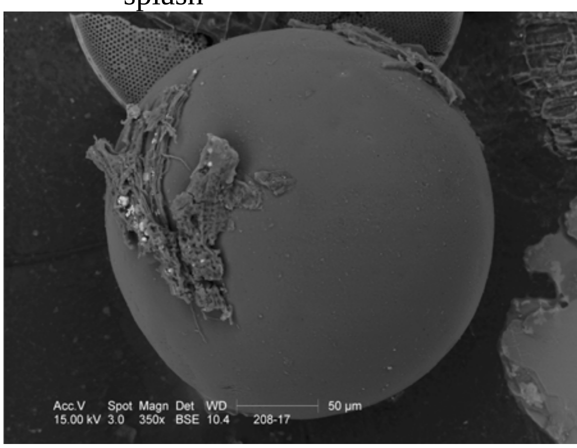


Figure 5. Chemical composition of spherule in Figure 4

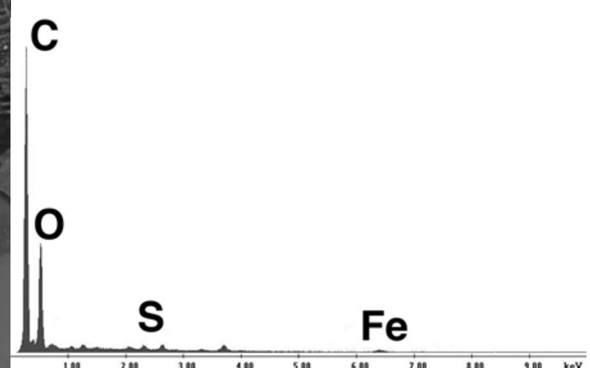


Figure 6. Close-up of pyrite splash on Figure 4

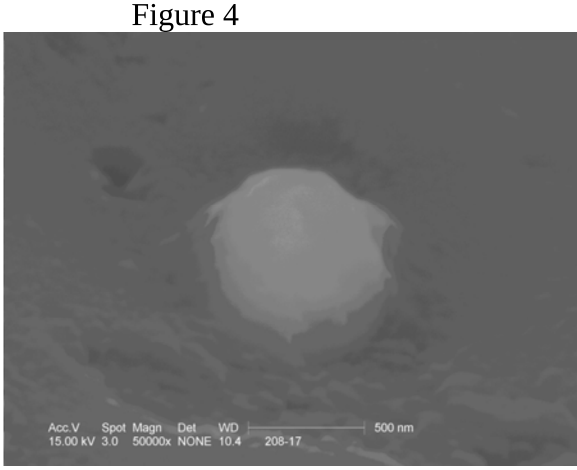


Figure 7. Chemical composition of pyrite in Figure 6

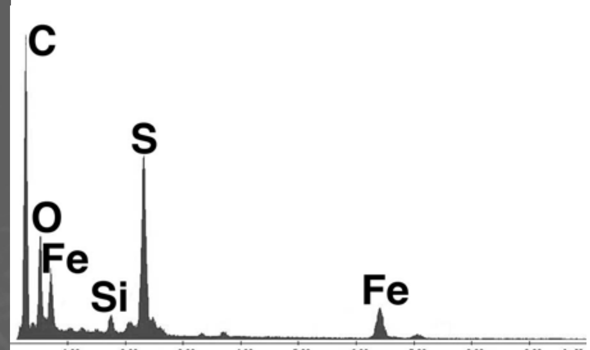


Figure 8. Carbon spherule with pyrite microspherules

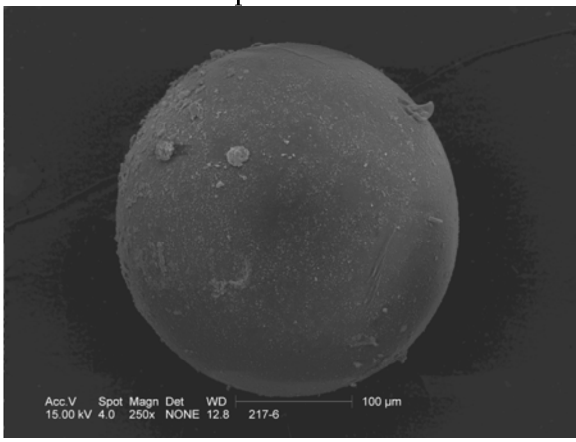


Figure 9. Chemical composition of spherule in Figure 8

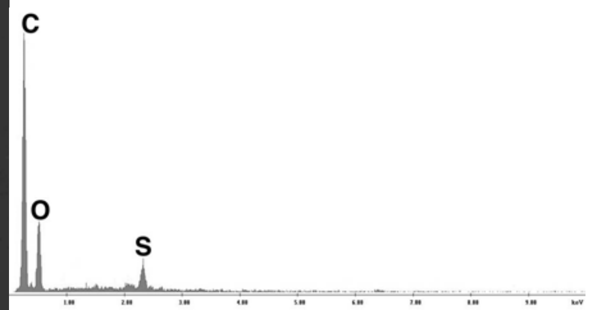


Figure 10. Close-up of microspherules on Figure 8

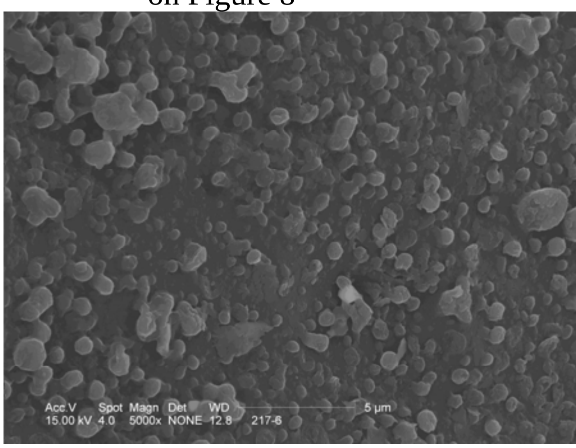


Figure 11. Chemical composition of microspherules in Figure 10

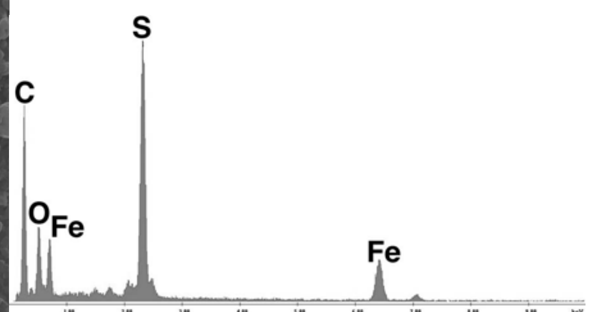


Figure 12. Iron oxide spherule with quench texture

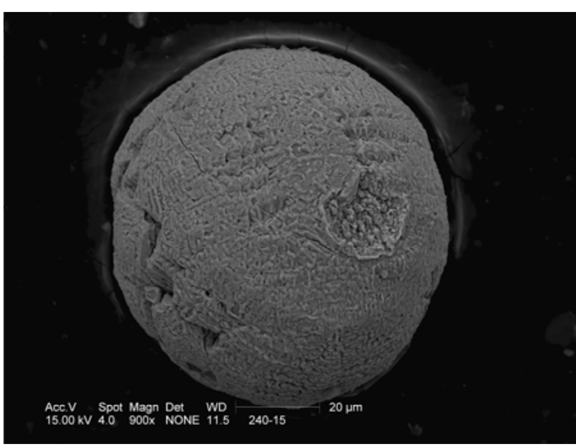


Figure 13. Chemical composition of spherule in Figure 12

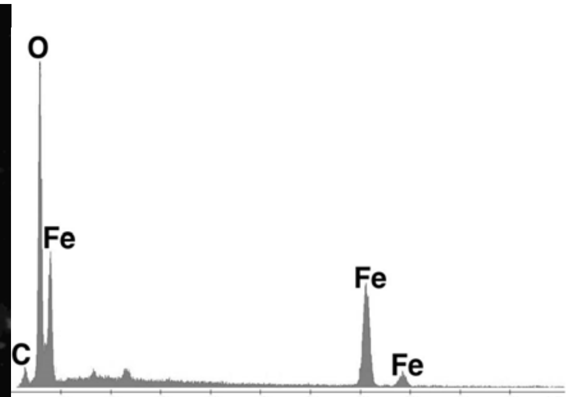


Figure 14. Smooth aluminum silicate spherule

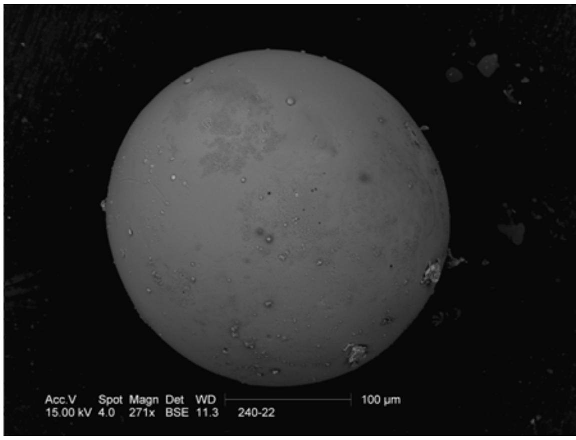


Figure 15. Chemical composition of spherule in Figure 14

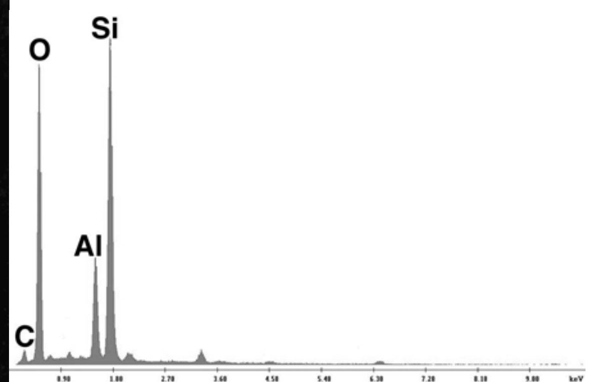


Figure 16. Aluminum silicate spherule with quench texture

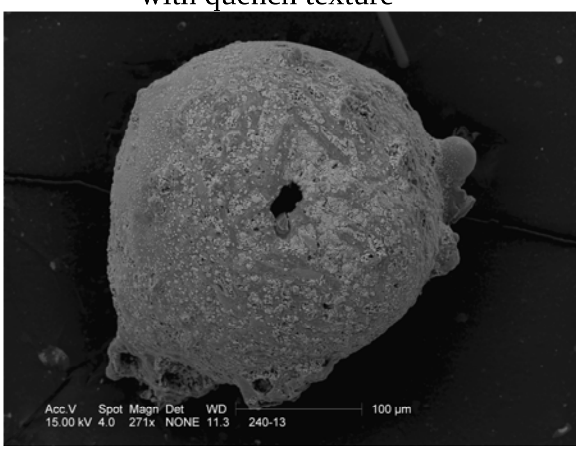


Figure 17. Chemical composition of spherule in Figure 16

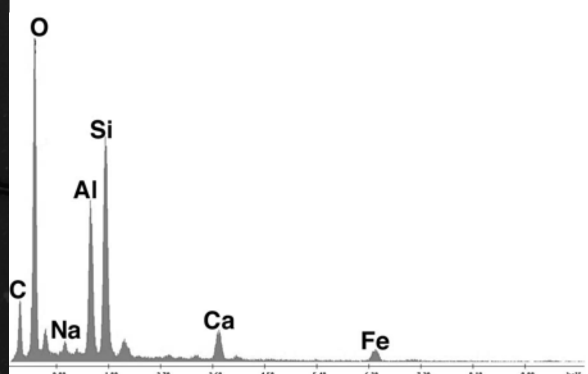


Figure 18. Close-up of quench texture on Figure 16

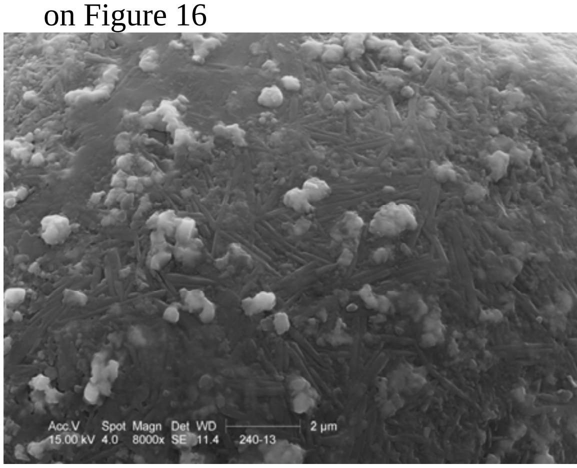


Figure 19. Chemical composition of surface in Figure 18

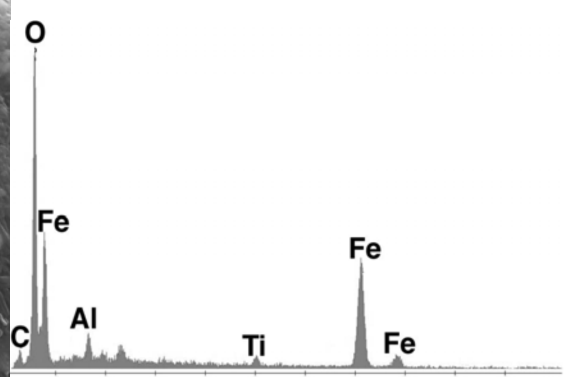


Figure 20. Joined aluminum silicate spherules with ilmenite needles

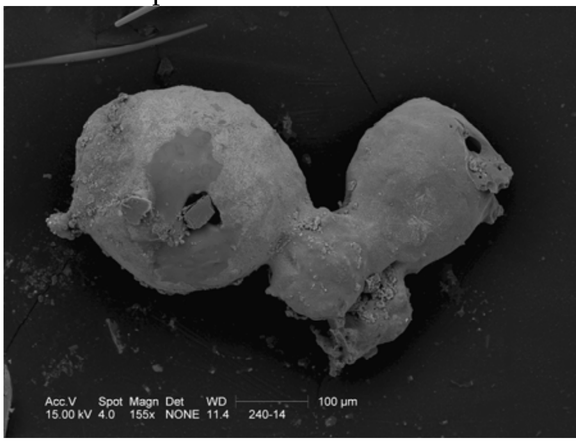


Figure 21. Chemical composition of spherules in Figure 20

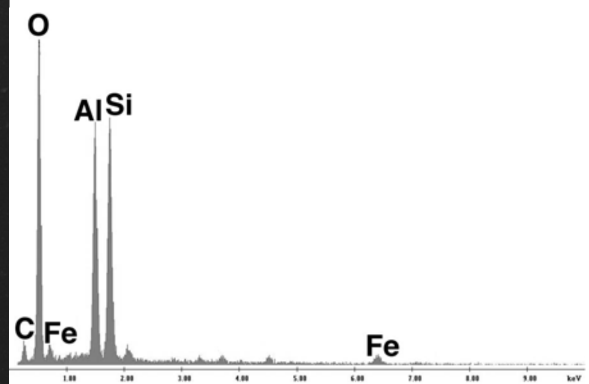


Figure 22. Close-up of ilmenite needles on Figure 20

Figure 23. Chemical composition of needles and substrate in Figure 22

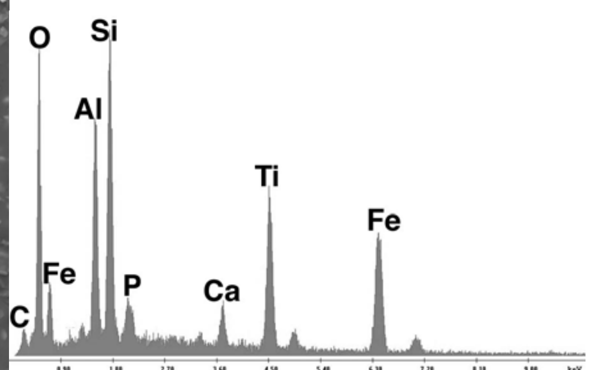


Figure 24. Shocked feldspar with Brazil twins

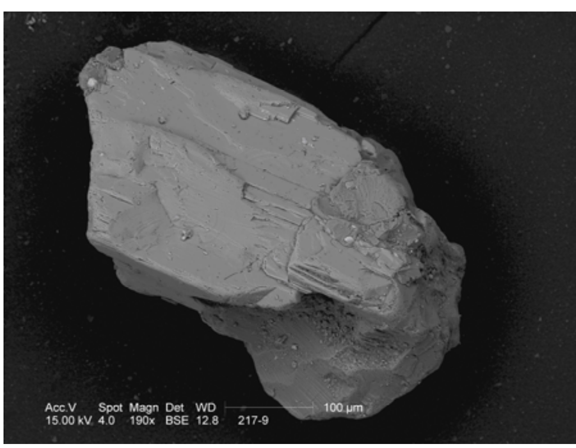


Figure 25. Chemical composition of feldspar in Figure 24

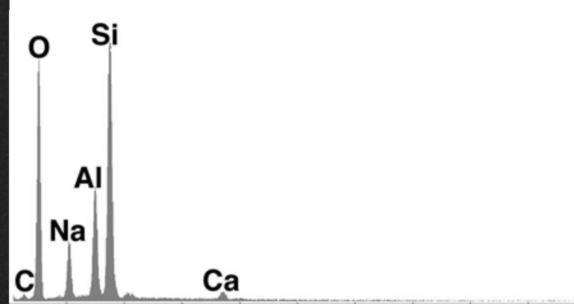


Figure 26. Close-up of Brazil twins on Figure 24 #1

Figure 27. Close-up of Brazil twins on Figure 24 #2

Figure 28. Olivine with planar features

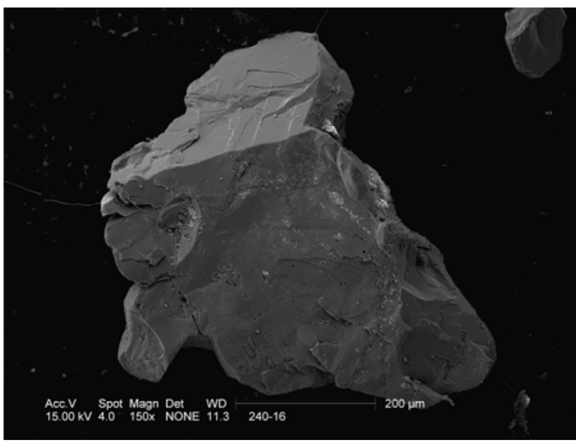


Figure 29. Chemical composition of olivine in Figure 28

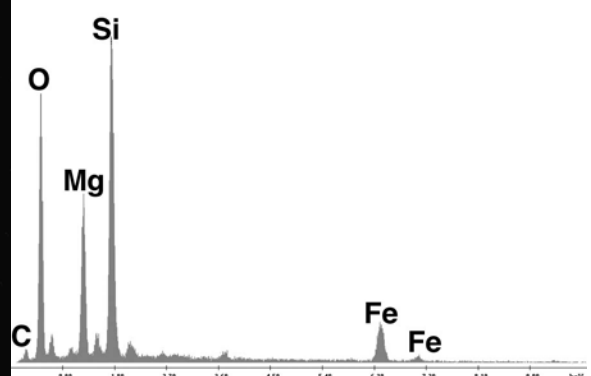


Figure 30. Close-up of planar features on Figure 28

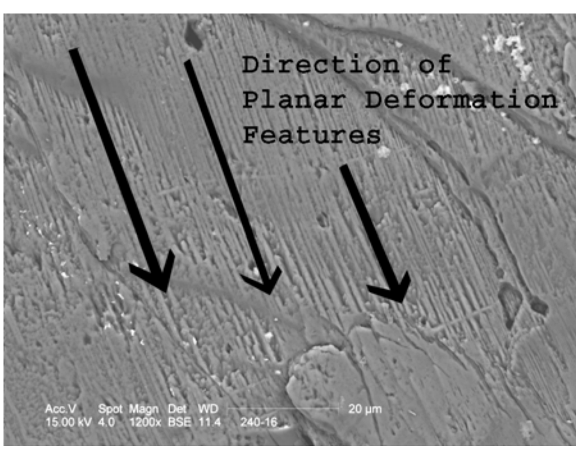


Figure 31. Chemical composition of planar features in Figure 30

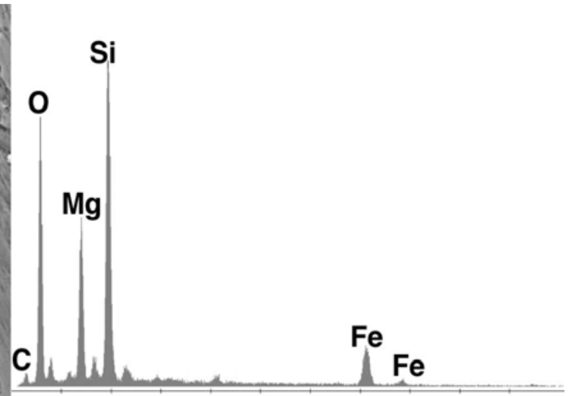


Figure 32. Shocked ilmenite breccia

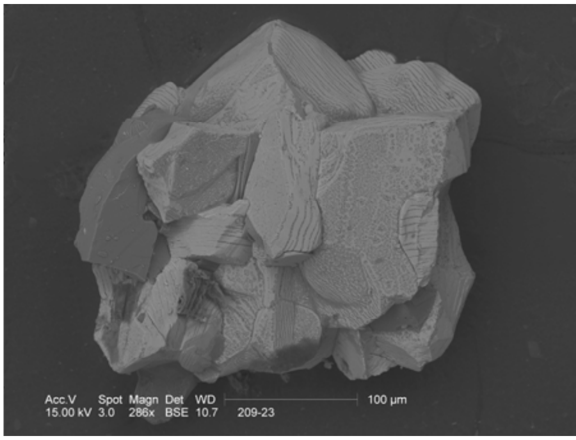


Figure 33. Chemical composition of breccia in Figure 32

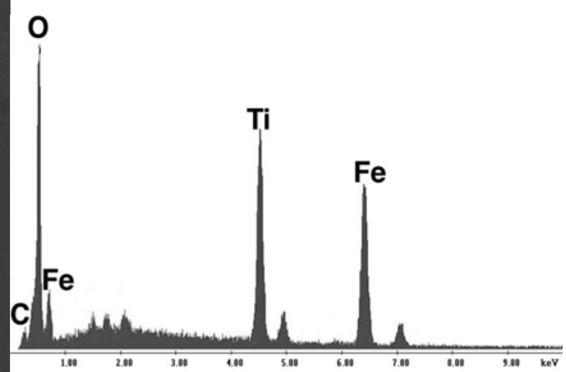


Figure 34. Nanodiamond #1

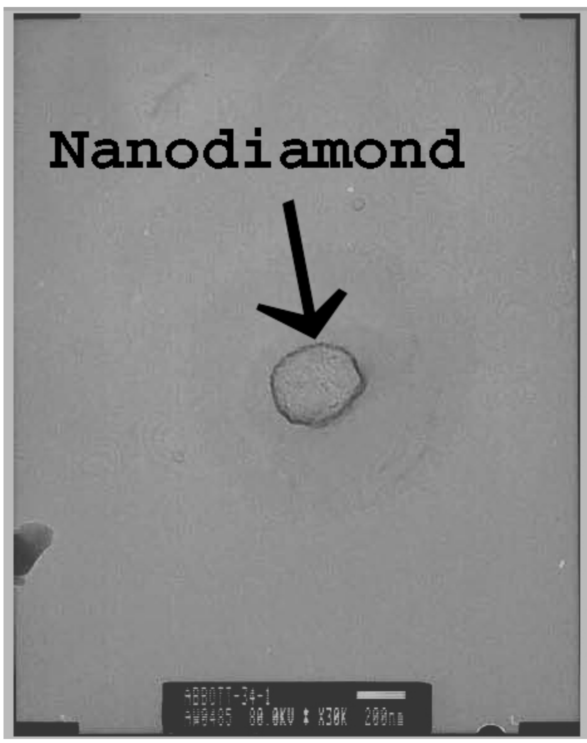


Figure 35. Electron diffraction pattern of nanodiamond in Figure 38

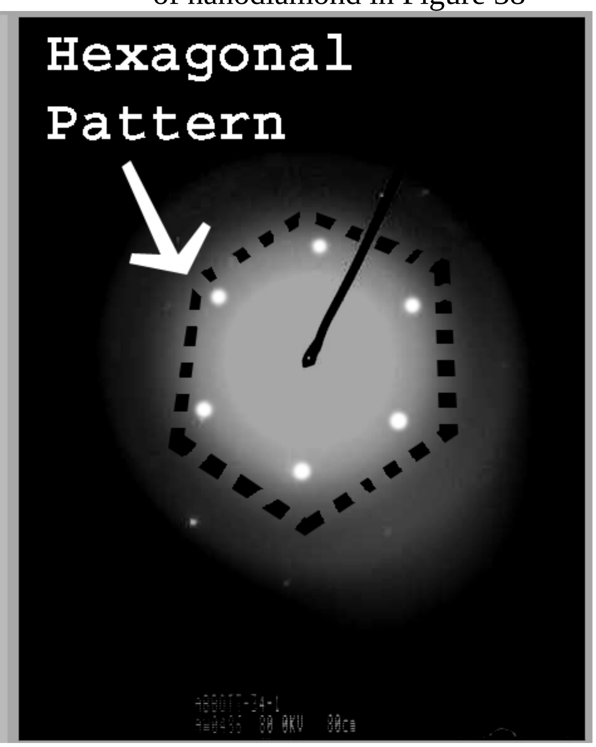


Figure 36. Nanodiamond #2

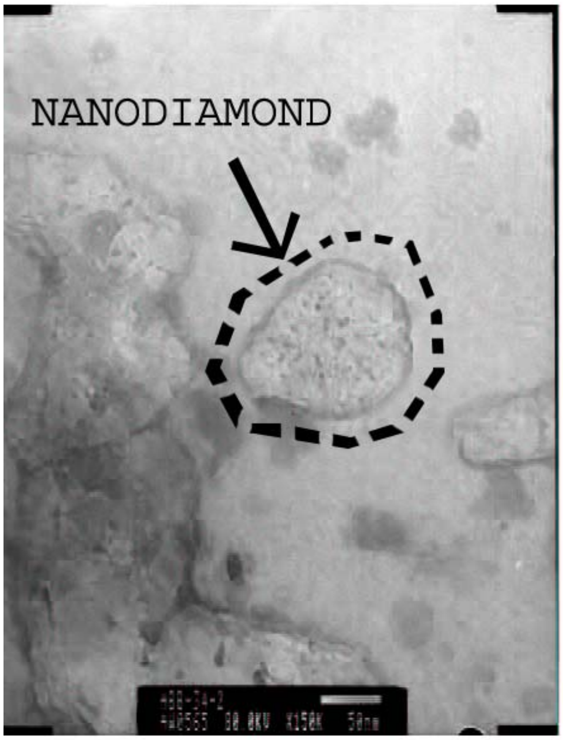
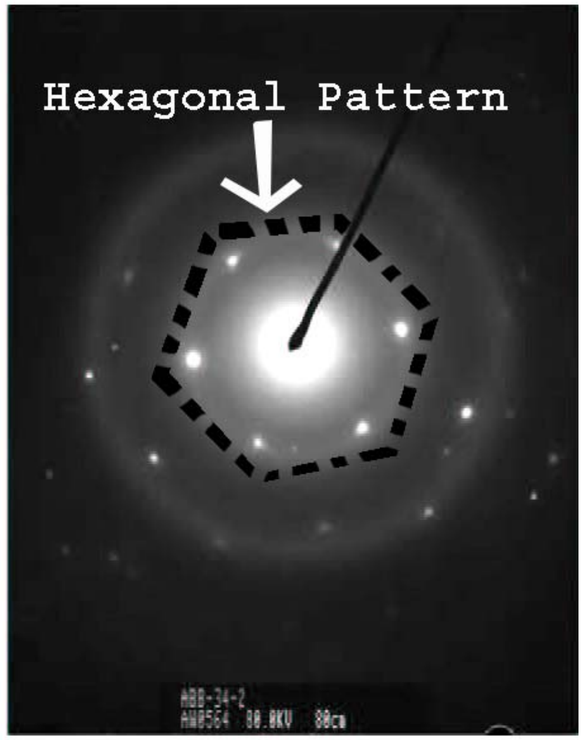


Figure 37. Electron diffraction pattern of nanodiamond in Figure 36



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